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U. S. Naval Civil Engineering
Laboratory
Port Hueneme, California

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AN ION GUN FOR A TIME-OF-FLIGHT MASS SPECTROMETER

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Type C

by

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ABSTRACT

There is a need at this Laboratory to develop an electronic method of chemical analysis which is versatile, fast, and inexpensive. An ion gun has been built for use in a proposed time-of-flight mass spectrometer; this spectrometer could be used for reasonably accurate analysis and would require considerably less cost to operate and maintain than the Laboratory 180^{o} spectrometer.

Details on the design and performance of the ion gun are given. Testing of the gun has shown that its sensitivity is 10^{-14} amp. per micron of inlet pressure for an unchopped ion beam. At a chopping frequency of 10^{4} pps and a pulse width of 10 nanoseconds, the sensitivity would be large enough for an electron-multiplier ion detector. A mathematical analysis of the proposed TOF spectrometer is given in the Appendix.

INTRODUCTION

As part of a program for developing a simple, easy-to-operate, analytical mass spectrometer, an ion source has been constructed for use in a non-magnetic time-of-flight (TOF) spectrometer. This ion source is patterned after the Nier ion gun used in the 180° analytical mass spectrometer of Consolidated Electrodynamics Corporation (CEC).

The need for fast reliable analyses of materials in the gaseous and solid state has always existed at this Laboratory. Although a precision emission spectrograph and 180° analytical mass spectrometer are available here, these instruments are not suitable for the quantitative analysis of samples which are submitted only occasionally and which differ markedly in chemical character from one to the next. The emission spectrograph and 180° mass spectrometer have been of critical necessity in programs[1,2] in which large numbers of samples of similar chemical composition or physical type have been studied over an extended period of time.

A non-magnetic TOF mass spectrometer, using simple pulse-generating and ion-detection circuitry has been proposed and is described in the Appendix. It would be useful for the rapid analysis of gases and solids with an accuracy under 10%. It would not require preparation of analytical standards and working curves for each sample type, as is done for an emission analysis in which sample composition has a marked effect on spectral intensity of each constituent[1]. Moreover, a mass spectrometer of this type would not require an amount of time on the order of 2 or 3 days to bring the instrument to operating status. This is the time usually required to put the CEC 180° spectrometer[2] into operation after it has been shut down for at least a week; this is a particular disadvantage in a laboratory where samples are submitted for analysis only occasionally. Another disadvantage of the CEC spectrometer is the massive electromagnet, the excessive size and weight being dictated by the ion beam radius of several centimeters which is needed for the high resolution produced by this spectrometer. A non-magnetic TOF spectrometer completely eliminates the need for a precisely controlled magnetic field of large cross-section; with solid-state electronics, a TOF instrument could probably be packaged into a unit weighing a few hundred pounds -- as contrasted to the weight of the CEC spectrometer which is of the order of tons. In fact, non-magnetic spectrometers are noted for their relatively small weight and size. For example, a radio-frequency non-magnetic mass spectrometer has been reported[3] which weighs under 25 pounds, including drift tube and all electronic circuits and power supplies. This type of instrument has been used in rockets for direct measurement of upper-atmosphere constituents.

The main disadvantage of non-magnetic TOF spectrometers has been their limited resolution as compared to that of the more complex magnetic

instruments such as the 180° CEC spectrometer which produces good resolution from 2 to 700 amu. The Bendix time-of-flight spectrometer, however, is reported[4] to give good separation of mass peaks well beyond 100 amu and to produce useful resolution to around 300 amu. This would be more than sufficient for the chemical analysis of solids and most gases. The ion gun described in this report is similar to the source used in the Bendix instrument in that it employs electron bombardment for the production of ions and produces bunched ions by chopping the electron beam.

GENERAL REMARKS ON NIER ION SOURCES[5,6]

The orthodox Nier ion source produces ions by electron-bombardment of a gas, and has the major advantage of being able to hold the ion-beam energy within ± 0.05 ev. This homogeniety in ion energy is due principally to the fact that ionization takes place in an approximately field-free region. The vacuum-spark and gas-discharge ion sources, on the other hand, usually have an energy spread around 10^3 ev. These latter sources are not suitable for time-of-flight spectrometers where it is important for ions of a given mass to have as nearly as possible the same energy on leaving the accelerating region. The time-of-flight technique, analyzed in the Appendix, requires the maximum homogeniety in ion energy, to insure useful resolution of mass peaks.

Figure 1 is a schematic of the orthodox Nier source. Ionization takes place in chamber (c) which is enclosed except for the electron, gas-entry, and ion-exit ports; hence, the influence of external fields on the ions is negligible. Low-energy electrons, with energies of the order of 100 ev, are generated by the filament (f) and collected by the anode (p). Chamber (c) is held at the ionizing voltage with respect to filament (f) so that the electron energy is essentially constant within (c); the anode voltage is usually slightly higher than the chamber voltage. Ions produced by bombardment are injected into the accelerating region (a) by virtue of their thermal velocities and a small repelling voltage brought into (c) onto a pair of plates (r) on either side of the gas-entry port. Repeller voltages are not large enough (~ 10% of the ion-accelerating voltage) to seriously affect the ion-beam energy spread. Some bombardment sources use, instead of a repeller voltage, a drawing-out voltage immediately outside the ionization chamber.

For ionization by electron bombardment, the curve of ionization probability versus electron energy flattens out around 100 ev for most atoms and molecules, and mainly as the result of this, the Nier source allows intensity variations in the ion beam to be held to ± 0.05 percent. It would, however, not be possible to maintain this homogeniety in ion intensity without the presence of a small magnetic field parallel to the electron beam.

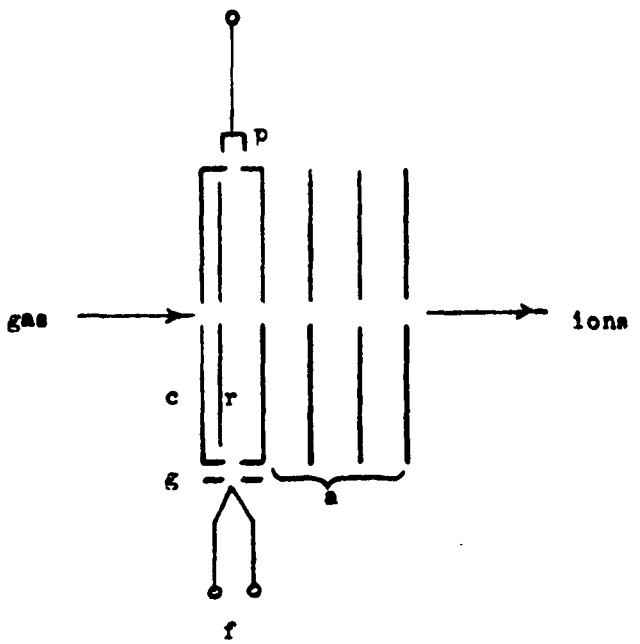


Figure 1. Schematic diagram of orthodox Nier source.

This constitutes a disadvantage of the Nier electron bombardment source, but the size of electromagnet usually required for collimation of the electrons is relatively small. Satisfactory collimation can be attained with field strengths as low as 100 gauss. Without a collimating field, secondary electrons produced by wandering electrons within the ionization chamber would lead to erratic intensity variations in the ion beam, and consequent loss of sensitivity, resolution, and analytical precision.

Insulation problems are not serious in the Nier ion source since, because of the small energy spread in ion energies, the accelerating voltages need only be around 10^3 ev. The composition of materials, used for fabrication of the ionization chamber and ion-accelerating plates, is not particularly critical; yet, it is important that sources be constructed of materials which are corrosion resistant, non-absorbing and non-magnetic. Non-magnetic stainless steel easily satisfies these requirements.

Design geometries in a Nier source are extremely critical if the source is to produce a focused beam of small cross section, as is required in magnetic spectrometers. In a source used for a non-magnetic time-of-flight instrument, careful alignment of accelerating and focusing slits is not important unless the ion-selection method is the electro-static deflection technique analyzed in the Appendix. Even here, slit alignment is not as critical as in the sources of magnetic spectrometers such as the CEC 180^o instrument. It is essential, however, that the electron slits be lined up with maximum precision in order to minimize production of secondary electrons and facilitate positioning of the external collimating magnetic field. Furthermore, the ionization region should be designed to produce the maximum signal-to-background intensity ratio. Hence, an electron-bombardment chamber should be tightly closed so as to give differential pumping effects allowing a given sample pressure to be maintained with minimum flow of sample.

In order that the Nier source can be used in a TOF spectrometer, such as the one analyzed in the Appendix, the ions must be supplied to the accelerating region in isolated groups. That is, the ion beam must be chopped. One way of doing this is to chop the electron beam by applying voltage pulses to a control grid (g) inserted between the filament (f) and the ionization chamber (c) as shown in Figure 1. Maximum resolution can be obtained by pulsing the drawing-out voltage as well as the control-grid voltage.

DESCRIPTION OF EXPERIMENTAL ION GUN

Design

Figure 2 is a cutaway view of the ion gun and vacuum housing

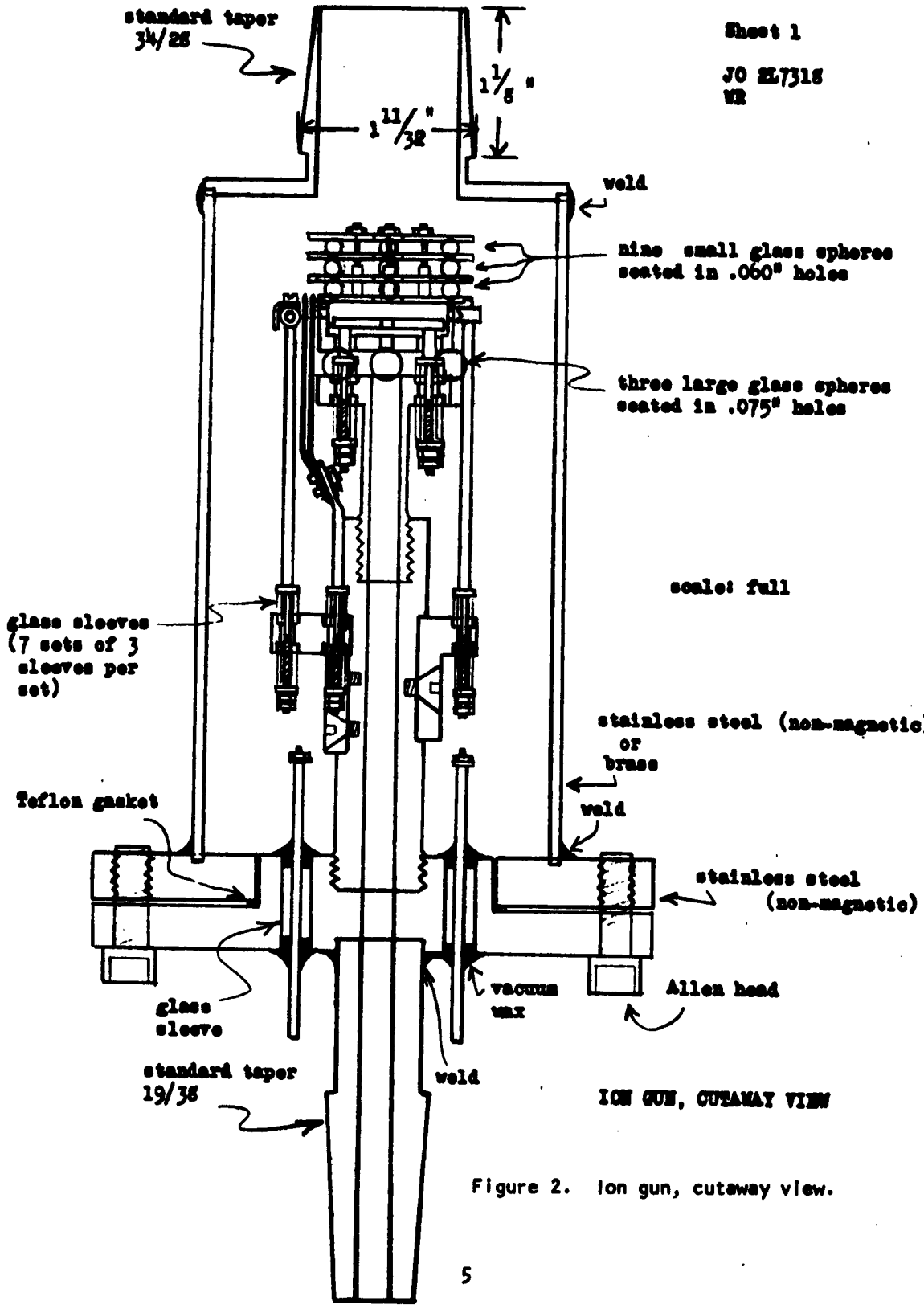


Figure 2. Ion gun, cutaway view.

constructed at the U. S. Naval Civil Engineering Laboratory. The design of this ion gun is similar to that of the source used in the CEC 180° mass spectrometer in that the ion-accelerating and focusing discs as well as the ionizing chamber are supported by glass spheres and held in place by stainless-steel rods, which pass through all these units and fasten to the accelerating disc. This disc is called the second accelerating disc because the lid of the ionizing chamber actually serves as the first accelerating disc. The design details of the rest of the ion gun, described in this report, are original with the author. This includes the electron-gun supports, the ion-gun mount, and the voltage leads in the base plate of the gun. The geometry and dimensions of the electron gun and accelerating region do not differ appreciably from those of other Nier sources. Figures 3 through 7 are sketches of the various sub-assemblies of the ion gun.

The ion gun sketched in Figure 2 and pictured in Figures 8 and 9, is constructed entirely of non-magnetic stainless steel and Pyrex glass, except for the filament, which is tungsten. The electrical leads for bringing in voltages to the gun are vacuum sealed into the base plate by means of Apiezon wax, type W. To prevent softening of these seals by heat from the filament, cooling water can be brought in thermal contact with the housing by copper tubing, welded to each end as shown in Figure 10. The tubing is welded to the housing at both ends because Apiezon wax is also used to seal the glass vacuum pump-out fitting which connects to the 34/28 standard taper shown in Figures 2 and 8.

The filament supports, electron-beam grids, anode, and repeller plate are isolated electrically from the ion gun by seven sets of glass sleeves, each set containing three sleeves of different lengths. By carefully squaring the ends of the sleeves on a carborundum wheel, it was found that each of these electrically isolated parts could be secured rigidly to the ion-gun mount without cracking the glass sleeves. The ion-gun mount is shown disassembled in Figure 3. The second accelerating disc and two focusing discs, shown in Figure 4, are held in place by nine glass spheres, approximately 3.5 mm in diameter. The two focusing discs are isolated electrically and depend solely on the glass spheres for support. The rods to the second accelerator disc pass through the focusing discs without touching.

The ionizing chamber consists of two parts as shown in Figure 5. It is isolated electrically from the rest of the ion gun in the same way that the focusing discs are isolated. Three of the 3.5 mm-diameter spheres are used to support the ionizing chamber. All the glass spheres in the ion gun are the type used for packing distillation columns. It was actually not possible to find two spheres whose diameters differed by less than 0.1 mm; however, it was still possible to rigidly mount the

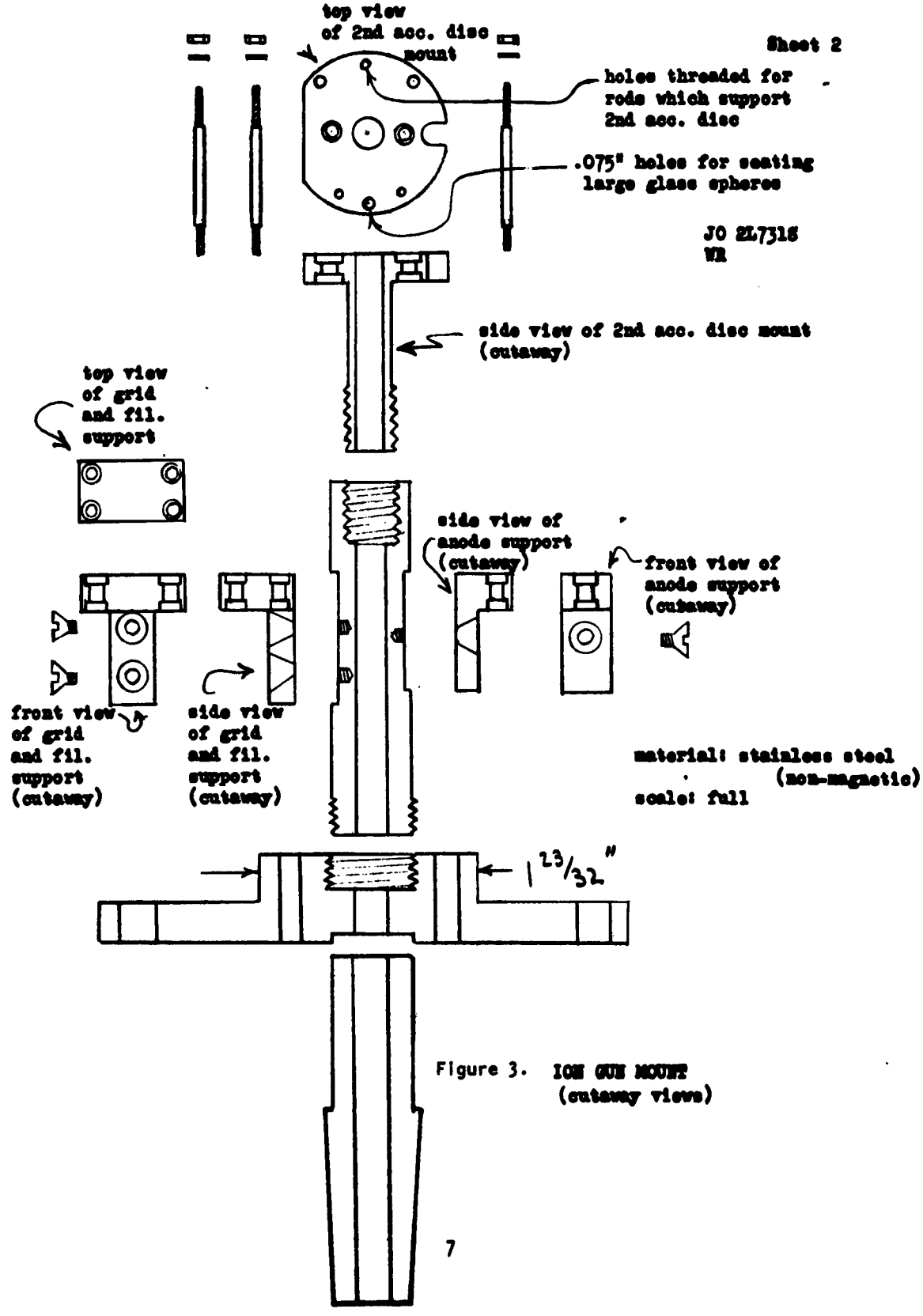


Figure 3. ION GUN MOUNT
(cutaway views)

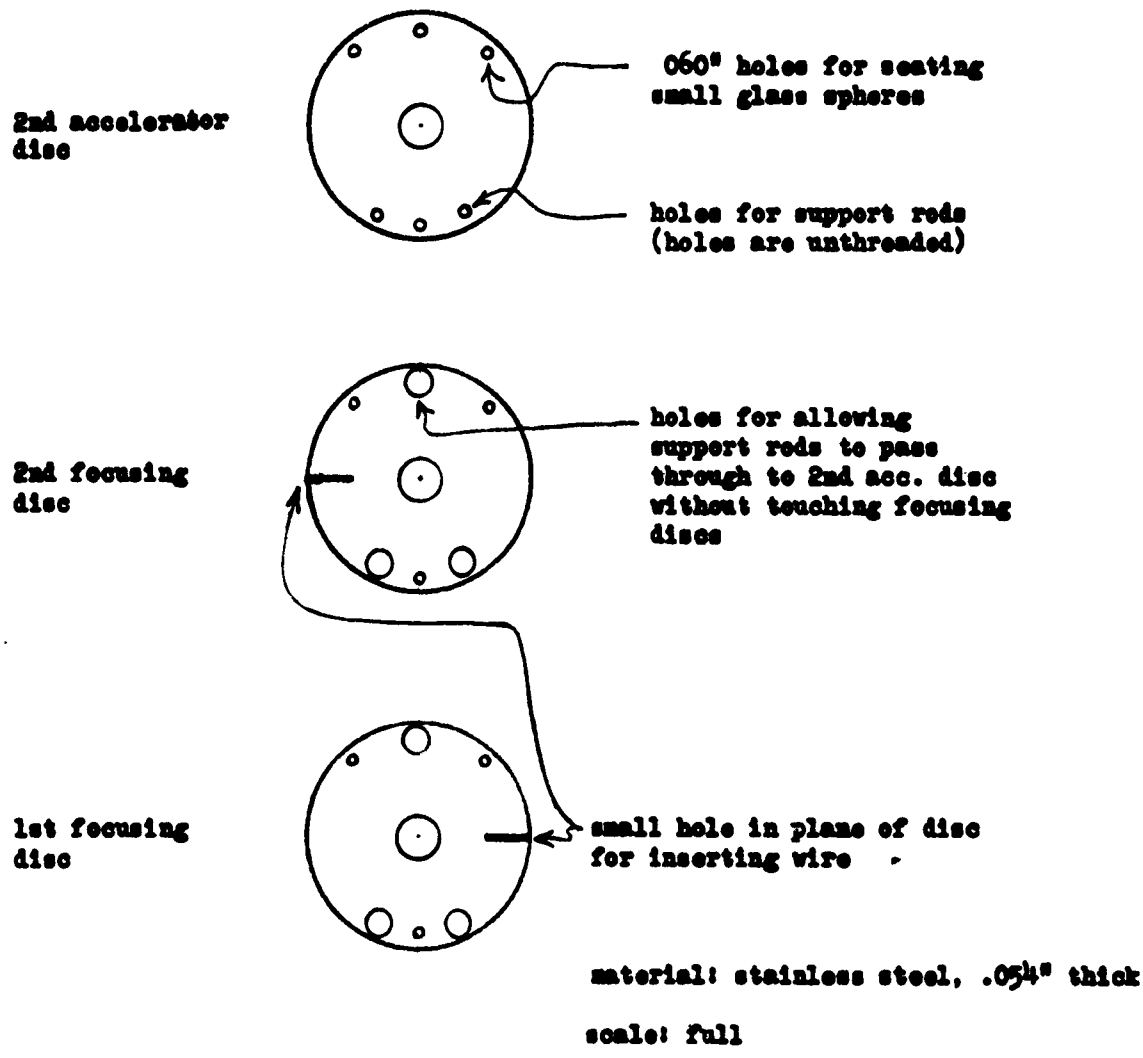


Figure 4. ION GUN PARTS

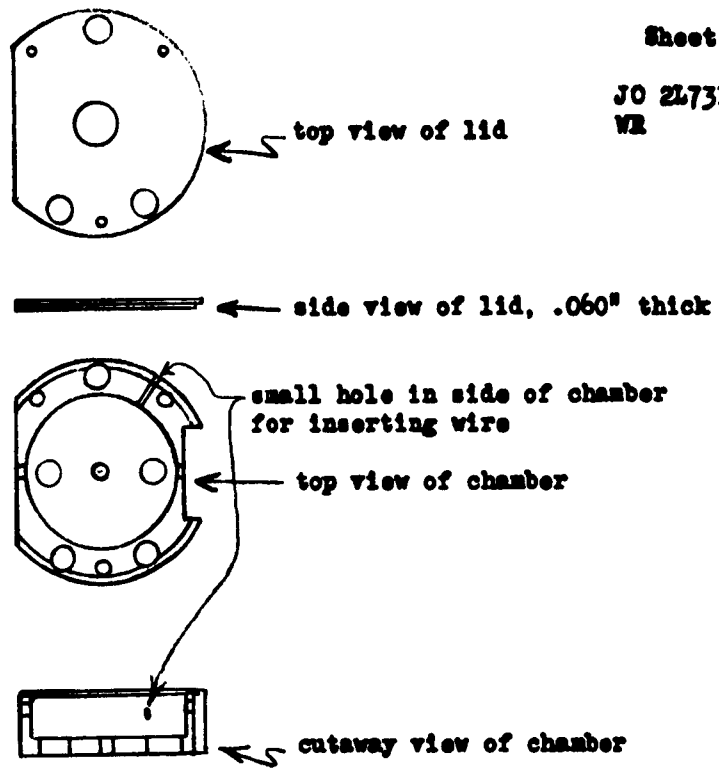


Figure 5. IONIZING CHAMBER

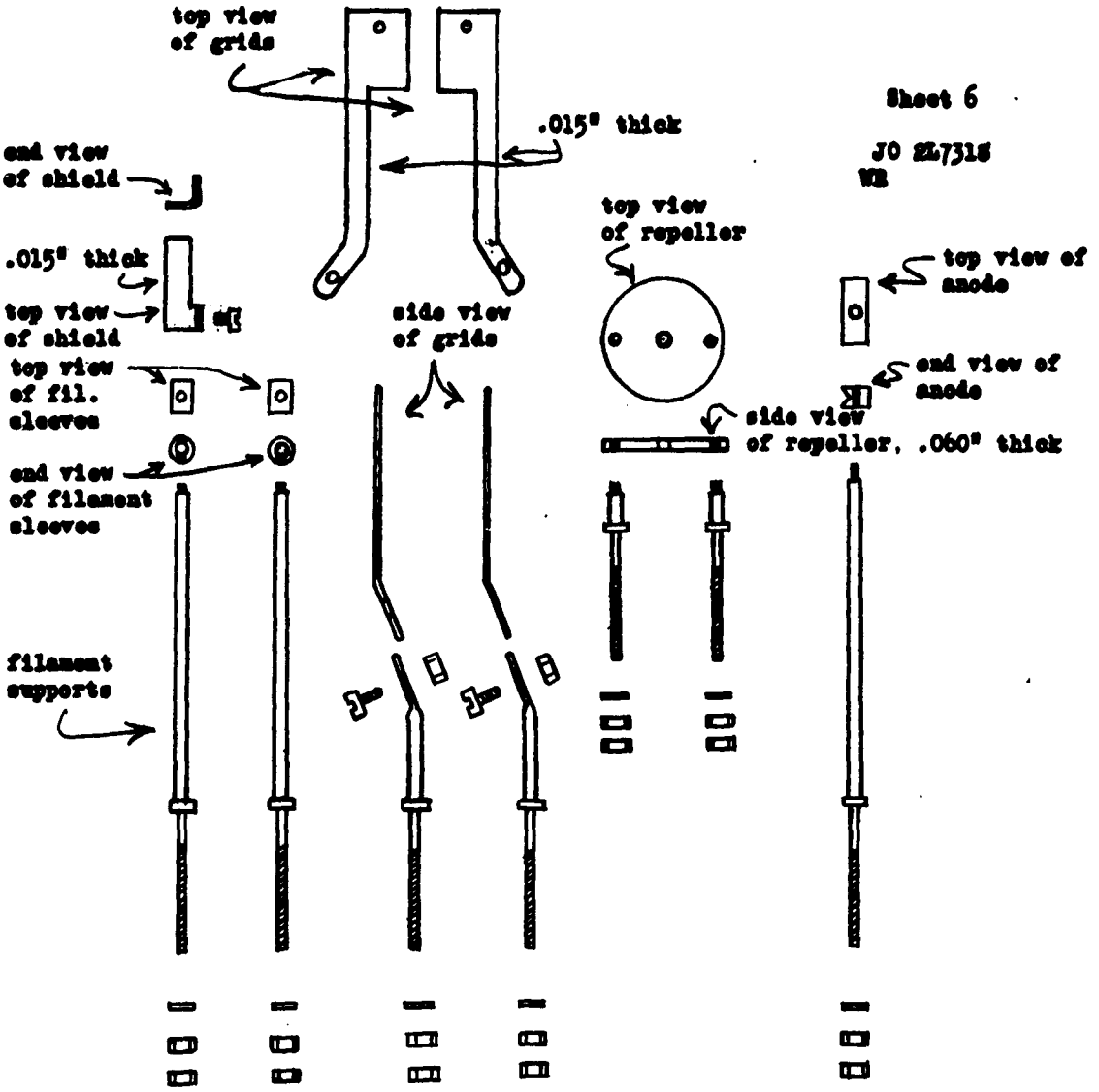
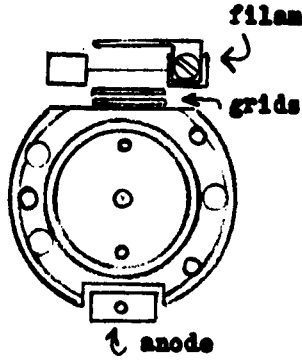


Figure 6. ION GUN PARTS

Note: filament is held in sleeves by small pieces of wire the same length as sleeves and diameter equal to slightly less than I.D. of sleeves so that .005" filament can be slipped inside. These small pieces of wire are held tight by threaded ends of the fil. supports.

detail view showing anode, grids, and filament with shield in place. Ionising chamber has lid removed showing repeller.



detail view showing filament supports and grids (small line between fil. sleeves represents .005" tungsten wire). Shield has been left out

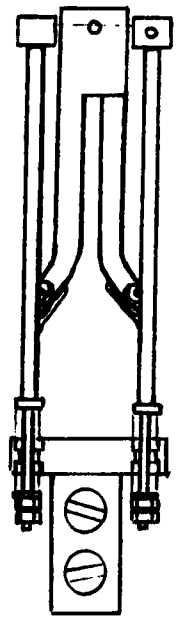


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Figure 7. ION GUN DETAILS

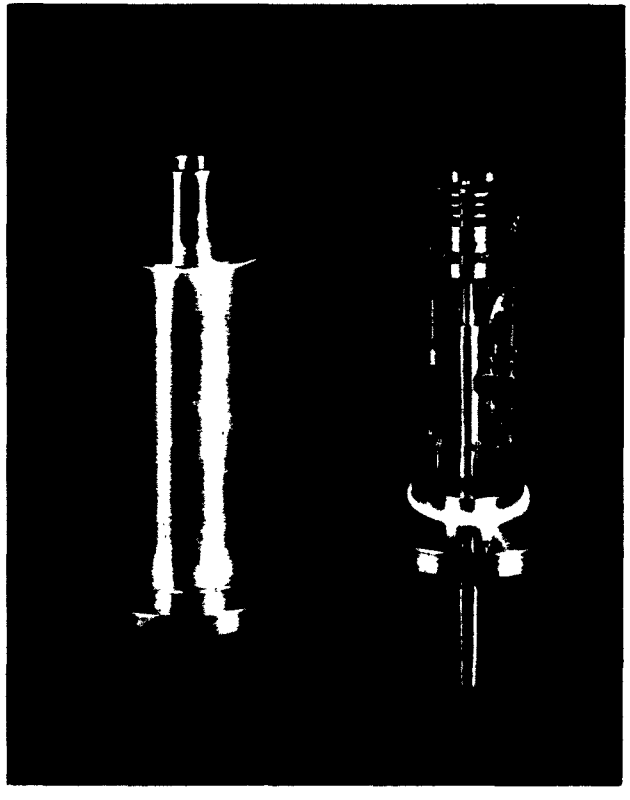

Figure 8. Partially assembled ion gun and housing.

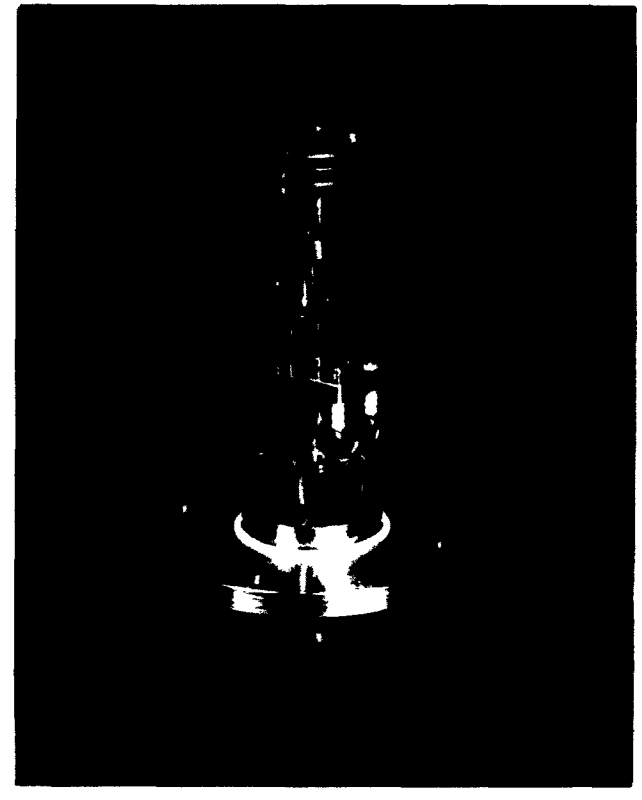

Figure 9. Ion gun completely assembled.

focusing discs and ionizing chamber. It was assumed that any adverse effects on the ion beam due to lack of parallelism in the discs could be eliminated by cutting asymmetrical slots in the focusing discs and supplying the proper voltage.

The various parts which constitute the electron gun are shown disassembled in Figure 6; details of the assembled electron gun are shown in Figure 7. The electron-generating filament is a tungsten wire, 0.125 mm in diameter and about 2 cm long, which is secured at each end inside a stainless-steel sleeve. Each end of the filament is held tightly against the inside wall of the sleeve by a short piece of stainless-steel rod inside the sleeve; the sections of rod are pressed against the filament ends by the threaded ends of the filament supports.

Two grids are installed between the ionizing chamber and the filament: one for chopping, the other for focusing. The focusing grid is included with the idea of eventually eliminating the external collimating magnet. An electron shield is attached to one of the filament-holding sleeves to increase ionizing efficiency.

The repeller assembly, shown installed in Figure 2 and disassembled in Figure 6, is electrically isolated from the ionizing chamber and the other sections of the ion gun by glass sleeves.

In Figure 8, the ion gun is shown assembled except for the copper wires connecting the various sections of the gun to the sealed-in leads in the base plate. The vacuum-tight gasket on the base plate is made of teflon. Figure 9 shows the assembled ion gun with all wiring in place; the insulating sleeves are glass tubing. In this photograph teflon washers have been temporarily substituted for the glass sleeves for the filament supports, and the electron focusing grid has been removed.

Figure 11 shows the gas-injection tube, which is constructed of Pyrex glass and connects to the 19/38 standard taper of the ion-gun mount (shown in Figures 2, 3, and 8). The dimensions of this tube are such that, when it is installed, the small tube, ring-sealed to the female taper, enters the ionizing chamber and terminates just short of the electron beam.

Performance

Figure 12 is a schematic of the circuitry used to operate the ion gun. The gun was attached, as shown in Figures 10 and 13, to a glass drift tube, approximately 100 cm long. The tube was wrapped in aluminum foil, which was connected to ground potential (the potential of the ion-gun

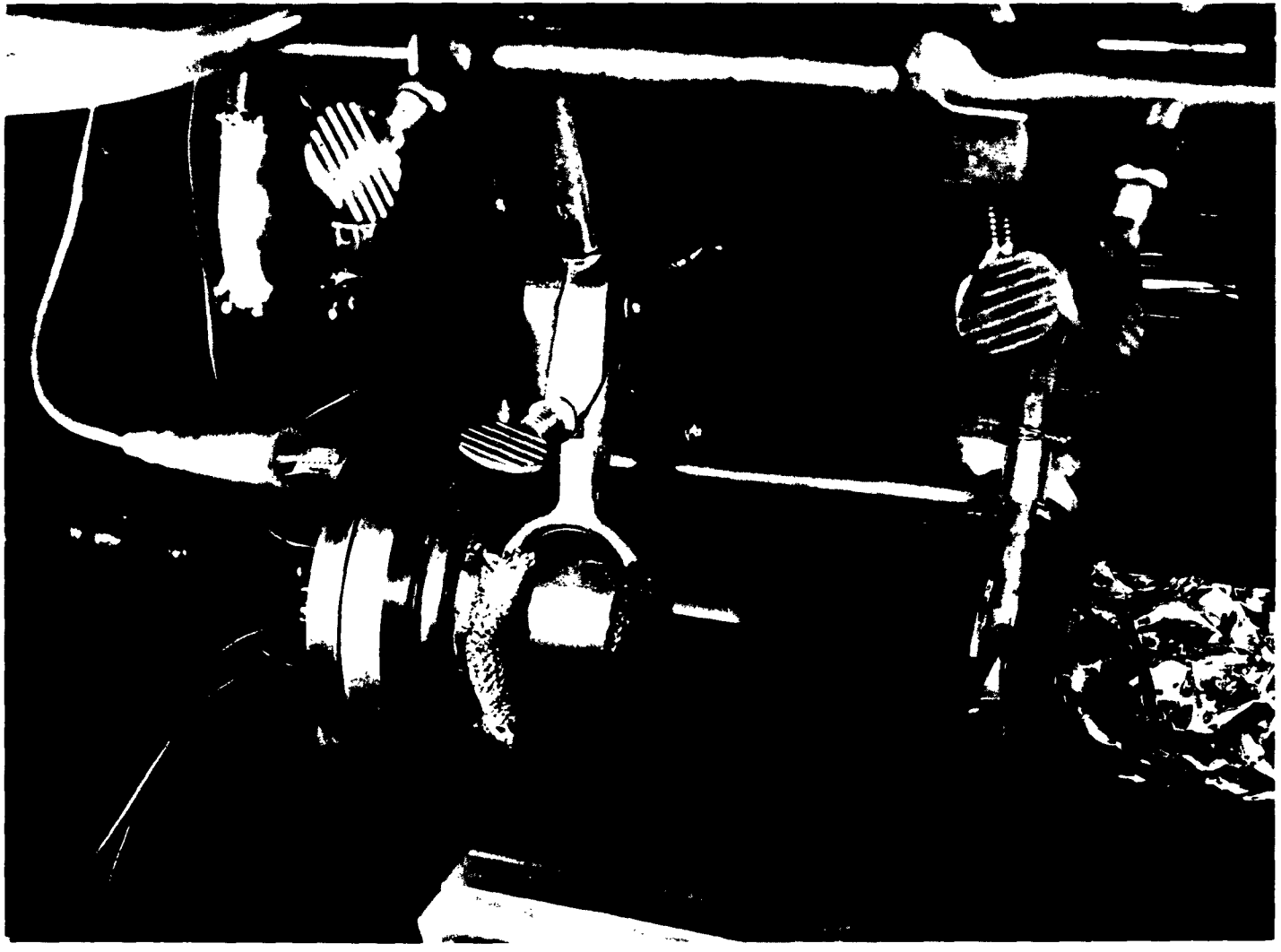

Figure 10. Ion gun installed in magnet.

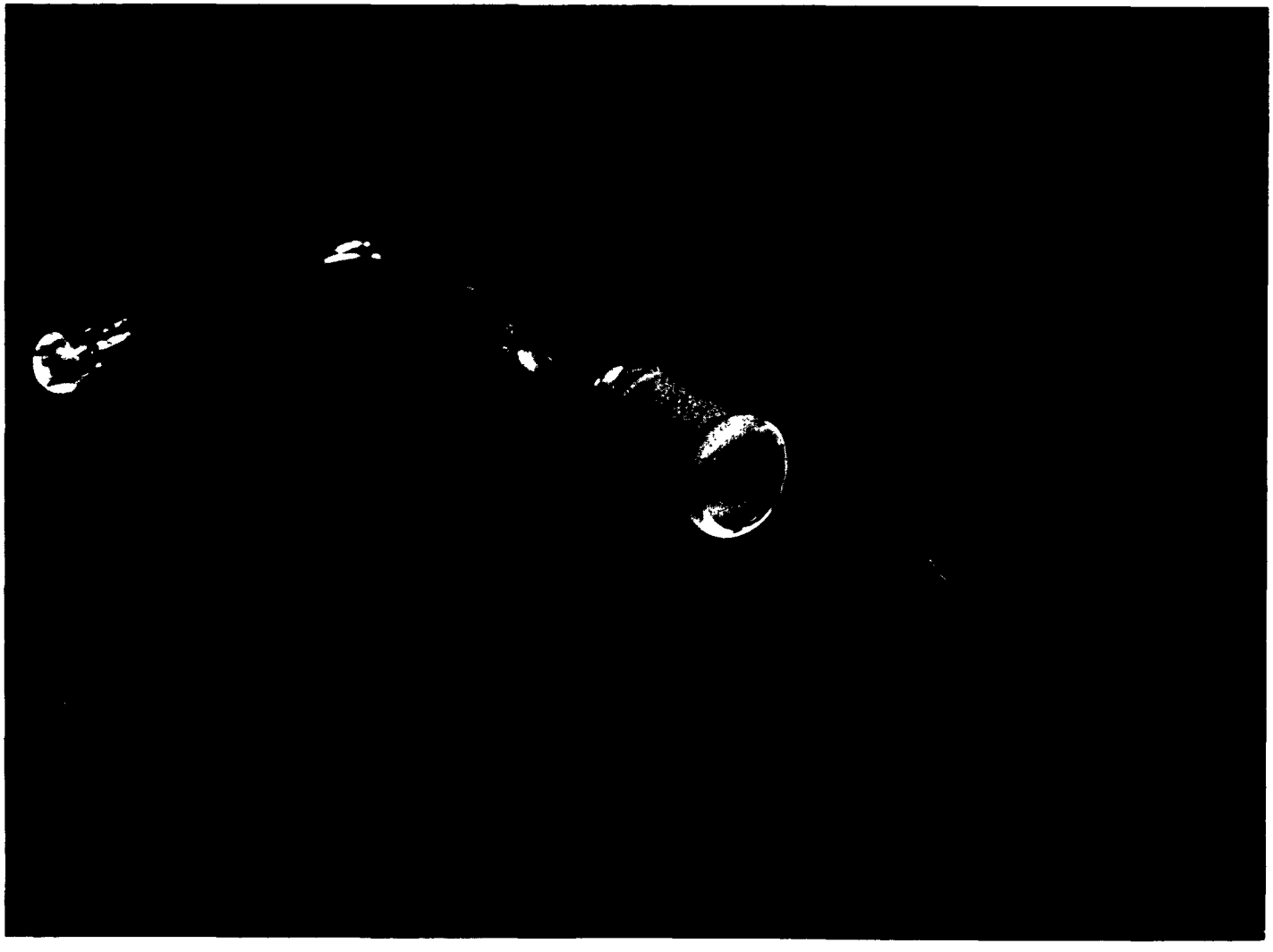

Figure 11. Gas injection tube.

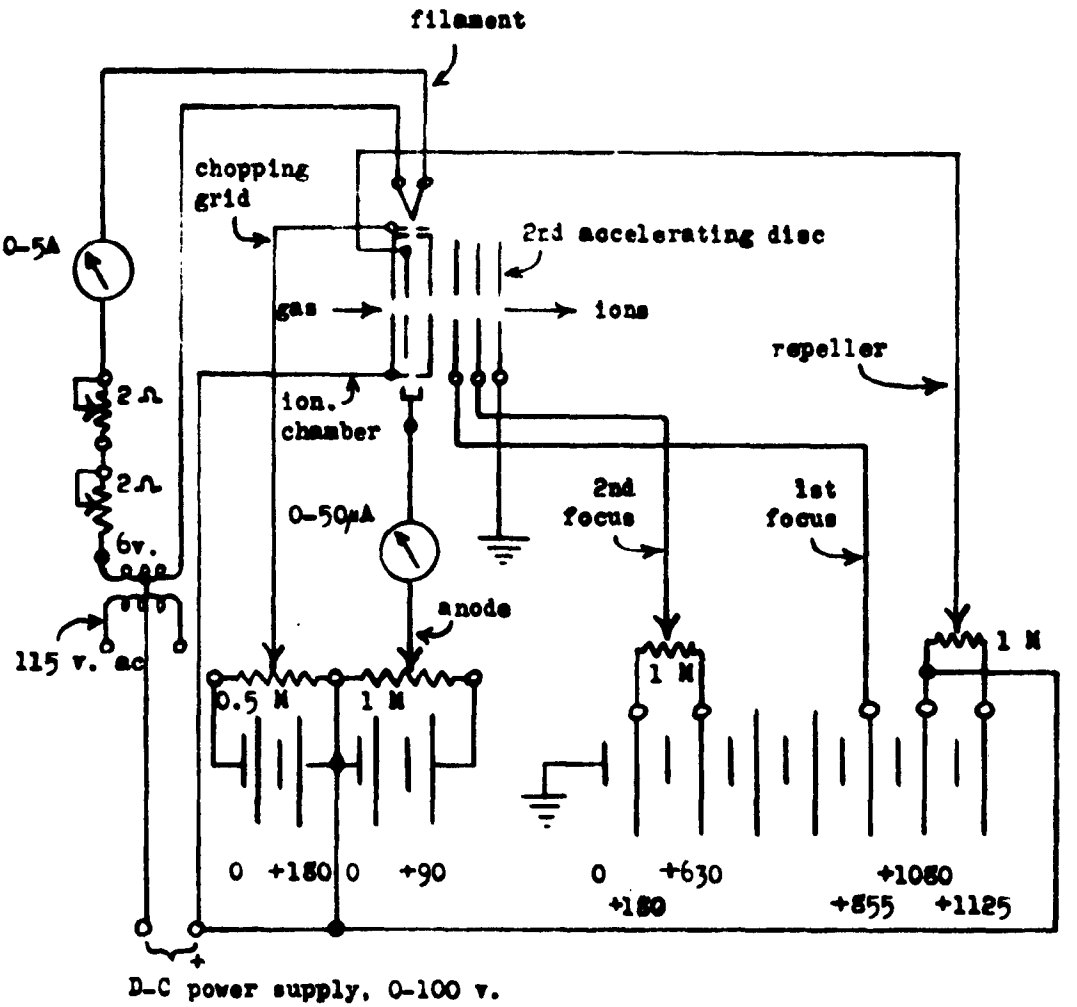

Figure 12. Circuit schematic for ion gun operation.

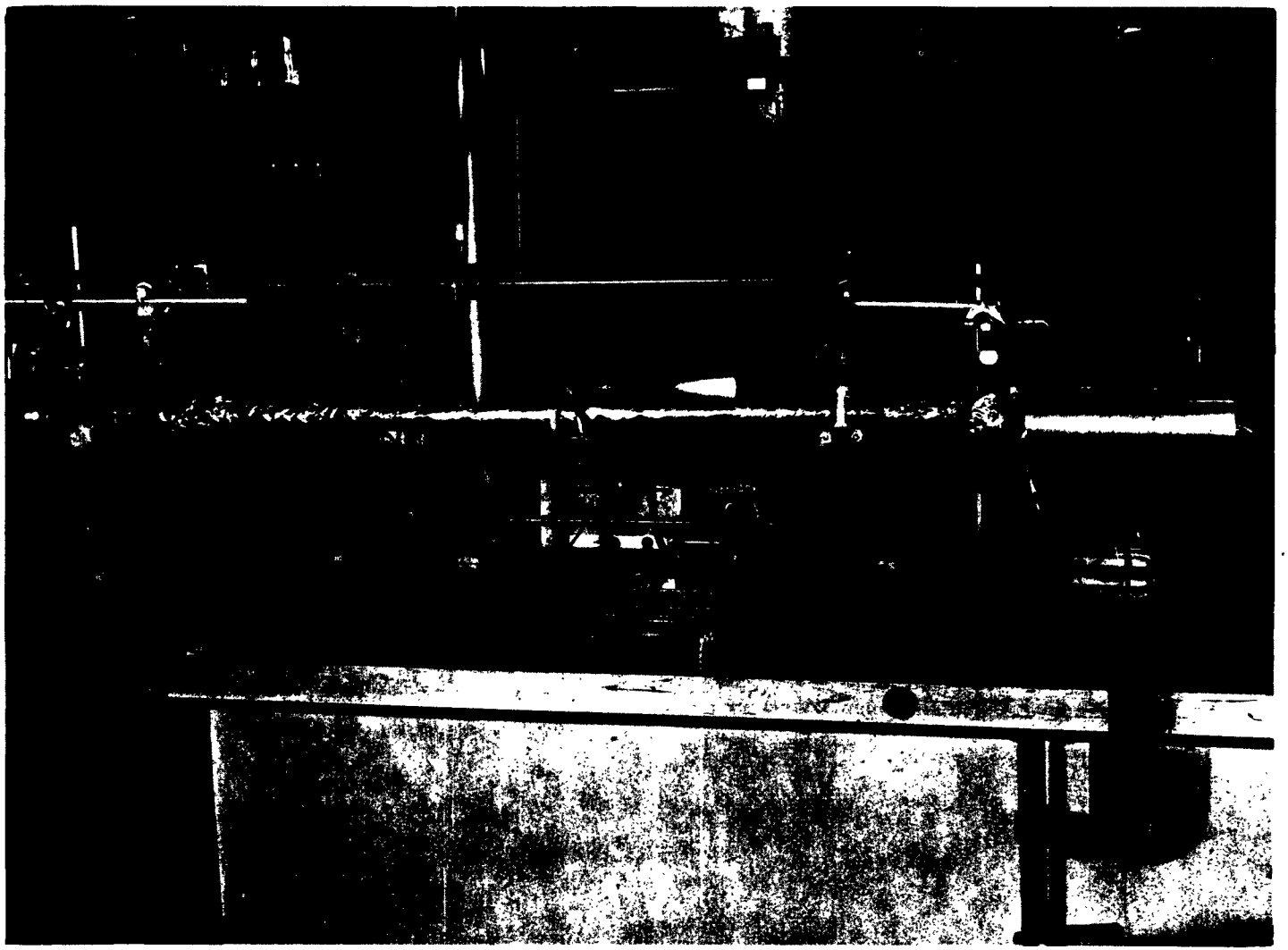

Figure 13. Magnet, drift tube, and electrometer.

mount and housing and the chassis of the ion detector). The purpose of the foil was to prevent build up of positive charges on the walls of the drift tube, causing deflection of the ion beam. In fact, without the foil, no ion current could be detected at the collector, located at the end of the drift tube. This was a small stainless steel cup, a few millimeters in diameter, connected to a tungsten wire. The tungsten wire passed through the glass to the grid of a type 38 electron tube. This could be used as the preamplifier stage of a simple electrometer by operating the plate and screen grid at approximately 10 volts and the filament at about 200 milliamperes, as is done in the CEC 180° mass spectrometer. Plate and screen voltages higher than 10 volts would cause ionization of the residual gas in the tube and destroy the high grid resistance needed for electrometer operation.

A vacuum system was connected to the drift tube at a point close to the output of the ion gun. A single-stage mercury diffusion pump with liquid-nitrogen freeze-out was used to attain vacua of around 10^{-6} mm Hg. A blending-type gas introduction system was connected, through a gold-foil leak to the gas injection tube; the leak was the type used by the CEC 180° spectrometer. The pump-out and introduction systems are pictured in Figure 14. Before the gun was put into operation, a leak was detected in one of the welded seams of the housing, evidently caused by either improper welding or the different expansion rates of brass and stainless steel; the housing base-plate and drift-tube fitting were stainless steel, and the body was brass tubing. A second housing was machined from a solid piece of brass. Leaking still occurred, but was remedied by coating the drift-tube end with Apiezon wax. The gun was tested with the solid-brass housing (water cooled as shown in Figure 10), and a third housing was constructed for future operations. This housing consists of a water-cooled stainless-steel base unit and a Pyrex-glass envelope with taper joints at each end: one for fitting onto the base unit, the other for connecting the drift tube. These items are pictured in Figure 15.

The electromagnet used for collimating the electron beam is the laboratory electromagnet of Atomic Laboratories, Inc. Special tapering pole pieces were machined and substituted for the large cross-section pole pieces which are supplied with the magnet. The magnet was operated at about 0.5 amp., producing a field estimated to be around 1000 gauss. Without the magnet it was not possible to collimate the electron beam with the focusing grid so that a measurable ion current was detected by the electrometer. The focusing grid was removed during testing of the ion gun.

Optimum operating conditions of the gun were the following:

1. Vacuum: 10^{-6} mm Hg

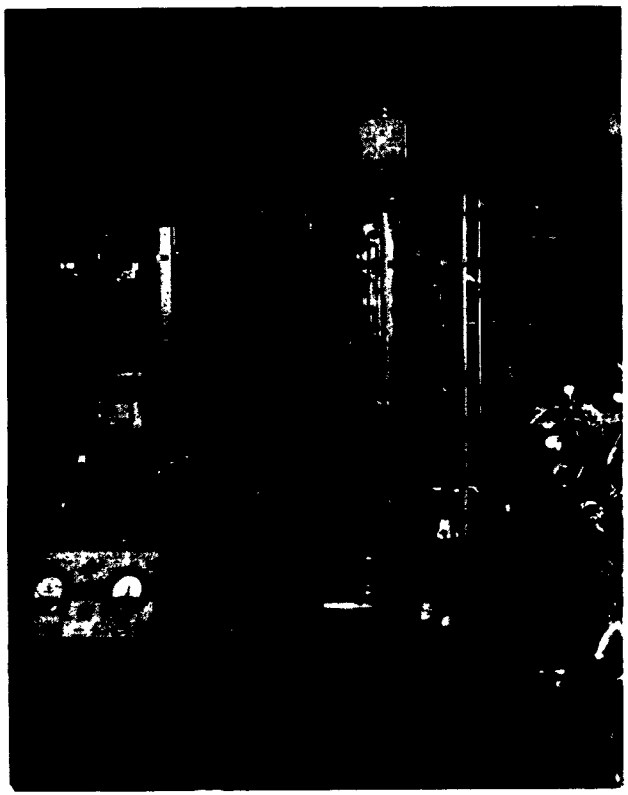

Figure 14. Gas introduction and pump out systems.

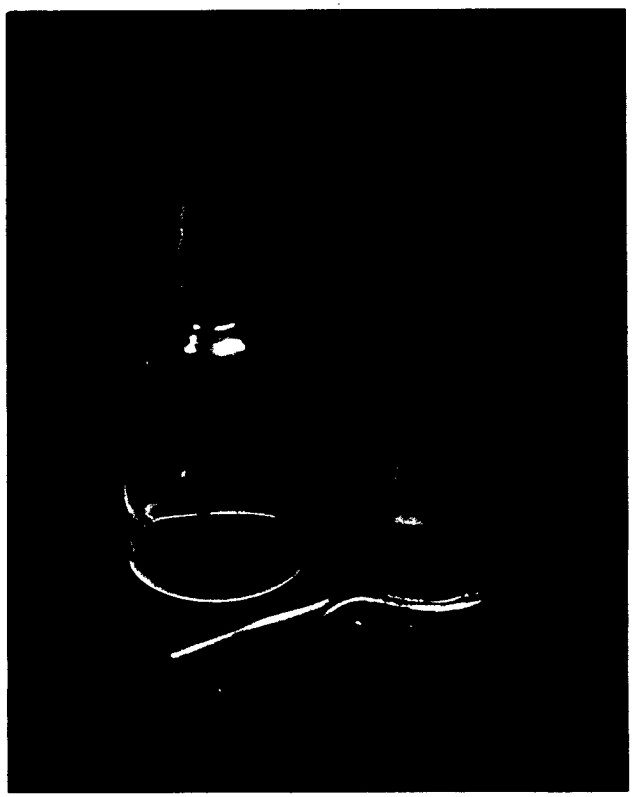

Figure 15. Glass ion-gun housing and base plate.

2. Filament current: 2.3 amps. (60 cycles)
3. Ionizing voltage: 90 volts
4. Anode voltage: 135 volts
5. Accelerating voltage: 1080 volts
6. Repeller voltage: 1100 volts
7. First focus voltage: 855 volts
8. Second focus voltage: 300 volts
9. Magnet current: 0.5 amp (~ 1000 gauss).

Voltages, 3 and 4, are with respect to the filament. Voltages, 5 through 8, are with respect to the second accelerating voltage which is at ground potential. A voltage was supplied to the chopping grid merely to measure the potential needed to cut off the electron beam. An increase in the chopping-grid voltage from 95 to 100 volts, caused the ionizing current (measured by the 0-50 μA meter shown in Figure 12) to drop from a maximum of approximately 20 μA to zero.

With the operating conditions listed above (the chopping grid being connected to the ionizing chamber) the sensitivity of the gun was estimated by measuring the output of the electrometer and the pressure of about 300 microns of air produced a 1/30 volt drop across the 10,000 megohm grid resistor of the 38 tube, which corresponds to $1/3 \times 10^{-11}$ amp. of ion-beam current. Hence, the estimated sensitivity is around 10^{-14} amp. per micron of inlet pressure. This sensitivity figure is a function of the leak diameter and the drift-tube length, in addition to the dimensions and operating parameters of the gun.

The ion gun was operated approximately 7 hours daily for 4 consecutive days; at the end of this period a short developed between the filament and the mount. Examination of the electron gun revealed that the filament wire had become loose at one end, permitting the filament to flex and touch the chopping grid.

CONCLUSIONS

Since no pulsing circuitry has been built for the ion gun, it is not possible to measure its resolving power. It can be concluded, however, that this gun would yield an ion current large enough to be detected by an electrometer if the chopping frequency were set equal to 10^4 sec $^{-1}$, which is compatible with the 10-nanosecond pulse width used in the Appendix and is of the order of frequencies used in the Bendix and other TOF instruments. From the estimated sensitivity of 10^{-14} amp./micron, determined by measurement of a steady ion current, the sensitivity for an electron beam, chopped at 10^4 pps into 10-nanosecond pulses, would be equal to, at most, 10^{-18} amp./micron.

Electrometers have been built[7] which will detect currents as low as 5×10^{-18} amp., yet it would be better to use an electron multiplier, which is known to easily measure currents of this magnitude and lower.

The sensitivity of the gun could be increased by installing suitable focusing discs for narrowing the ion beam and thus concentrating a larger proportion of ions at the selector entry port. By replacing the center-drilled focusing discs with discs in which off-center holes had been cut, and orienting the new discs to off-set the holes in opposite directions, right-left deflection and improved focusing of the beam would be possible.

The problem of the filament holders could be solved by spot welding to each end of the filament the short sections of rod held in the sleeves by screws. Evidently the trouble observed, during the testing of the gun, was due not to the short rods slipping out of the sleeves but to the tendency of the filament wire, itself, to slip out from between the rod and sleeve as the result of heating.

ACKNOWLEDGEMENT

The author wishes to thank Mr. Paul Peters, of the Laboratory Shops, for the excellent workmanship he put into the construction of this ion gun.

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APPENDIX

Analysis of a proposed TOF mass spectrometer.

The time-of-flight technique utilizes the fact that for an ion of a particular kinetic energy, its velocity, v, is a function of its charge-to-mass ratio, e/m. This follows from the well-known non-relativistic relation,

$$1/2\ mv^2 = eV \qquad (1)$$

where V is the ion-accelerating voltage.

A group of similarly charged ions subjected to a particular accelerating voltage will spread out along the direction of acceleration into separate bunches, the lighter masses leading the heavier ones. For low-energy bombarding electrons in the 100-ev range, singly-ionized positive ions are produced; hence, ion velocity can be correlated with mass alone, and e set equal to 4.8×10^{-10} esu.

If ion groups are injected into the accelerating region in succession, a mass spectrum can be read by capturing the separated bunches in a conventional ion collector which is connected to the vertical plates of an oscilloscope. A periodic voltage, synchronized with the injection pulse rate in the ion source and applied to the horizontal plates of the oscilloscope, would produce a spectrum on the cathode-ray screen readable directly in terms of mass number and ion intensity. This method of read-out is employed in the Bendix TOF spectrometer[4].

The technique for the TOF instrument, proposed for the ion gun described in this report, would employ electrostatic deflection of ion bunches at the end of the drift tube. An analysis of this idea is presented in section II of this Appendix.

1. Ion bunching

Infinitely fine resolution is possible only if the ions of each group, injected into the accelerating region, are all in the same transverse plane. In practice the ions of each group will be spread over a small distance, S, which is dependent on the duration of the electron-beam chopping-voltage pulses. If the ions are produced in a field-free region and the electron bunches producing these ions are of length, Δt, in time, then

$$S = v_T\ \Delta t \qquad (2)$$

where v_T is of the order of the mean thermal velocity of the neutral atoms at the temperature, T, of the ionizing chamber. That is

$$v_T = (kT/m)^{1/2} \tag{3}$$

where k is Boltzmann's constant.

The spread, S', of the ion group as it leaves the accelerating region is derived by computing the time, τ, for the first ion of the group to reach the point $X = X_a + S'$ as shown in Figure 16. Thus

$$\tau = t_a + \frac{S'}{v + v_T} \tag{4}$$

where t_a is the time for an ion of a given mass to traverse X_a. The time for the last ion in the group to traverse $X_a + S$ is also equal to τ; thus

$$\tau = \frac{S}{v_T} + t_a. \tag{5}$$

Hence, from (1), (2), (4) and (5),

$$S' = \left(\frac{v + v_T}{v_T}\right) S = \left[\sqrt{\frac{2eV}{m}} + v_T\right] \Delta t. \tag{6}$$

It can be assumed that the operating temperature of the ionizing chamber is around 250° C, since this is the case for the ion gun in the CEC 180° spectrometer. This means that $\sqrt{kT} \sim 2.5 \times 10^{-7}$. For $V = 10^3$ volts, $\sqrt{2eV} \sim 5.5 \times 10^{-5}$. Thus the thermal contribution to S' can be neglected and, from (6)

$$S' = \sqrt{\frac{2eV}{m}}\ \Delta t. \tag{7}$$

A plot of S'_i versus m_i for $\Delta t = 10$ nanoseconds is given in Figure 17 where the subscript, i is an integer beginning with 1.

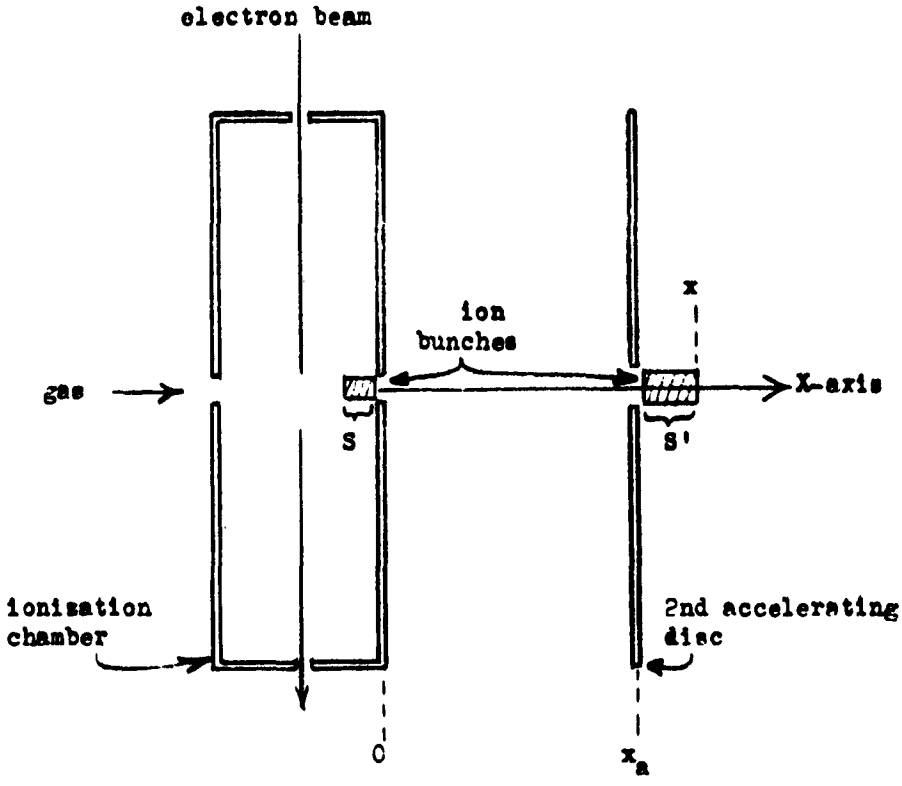

Figure 16. Schematic for ion bunching analysis.

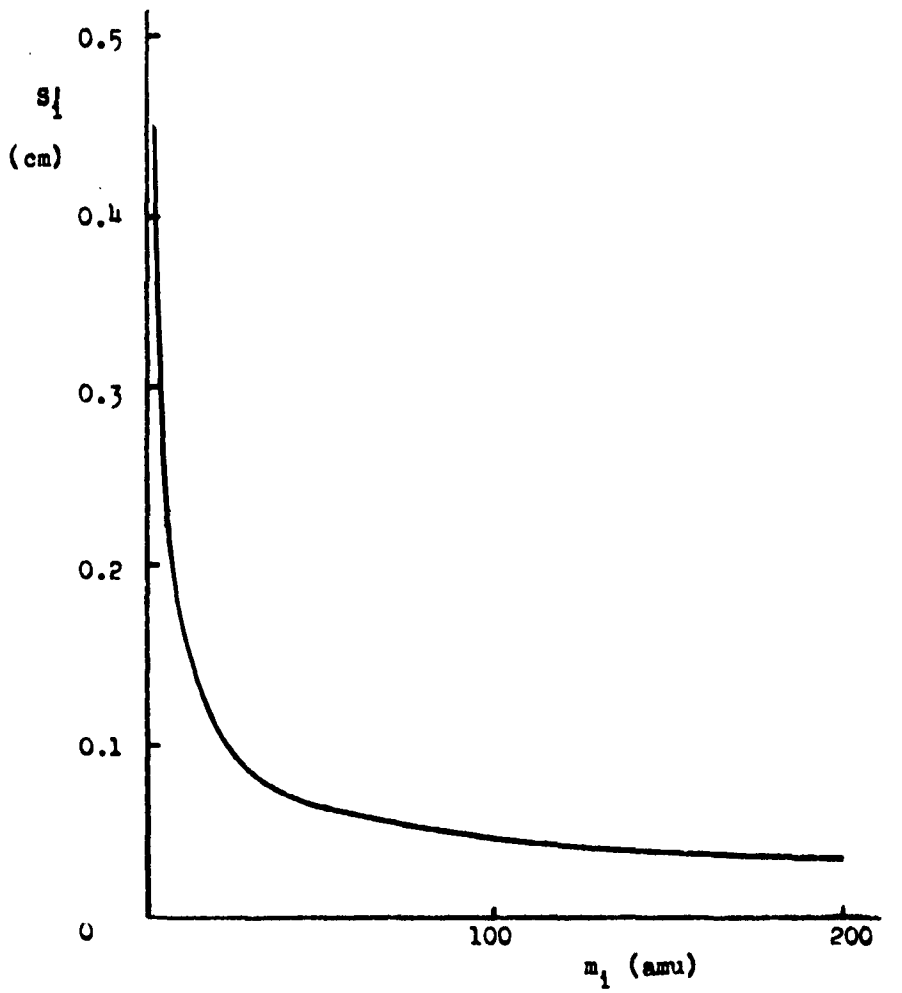

Figure 17. Ion bunch length, S_i', versus mass, m_i.

The separation, Δd, between the centers of ion bunches of successive masses, after bunch, i, has moved a distance, d, is

$$\Delta d = t_{di} (v_i - v_j) \tag{8}$$

where t_{di} is the flight time of mass m_i, and v_i and v_j are the respective velocities of the two bunches, i and j, which differ by one mass unit.

Thus, from equations (1) and (8),

$$\Delta d = \frac{d}{v_i} (v_i - v_j) = d \left(1 - \sqrt{\frac{m_i}{m_j}}\right). \tag{9}$$

The separation, ΔS, between the first ion of group, j, and the last ion of group, i, is from equations (7) and (9)

$$\Delta S_{ij} = d\left(1 - \sqrt{\frac{m_i}{m_j}}\right) - \frac{\Delta t}{2} \sqrt{2eV} \left(\frac{1}{\sqrt{m_i}} + \frac{1}{\sqrt{m_j}}\right). \tag{10}$$

A plot of ΔS_{ij} versus m_i (with $m_j = m_i + 1$) is given in Figure 18 where d = 100 cm, $\Delta t = 10^{-8}$ sec, and $V = 10^3$ volts.

It can be seen from Figure 18 that overlap of ion bunches at drift distance, d = 100 cm, does not occur until well beyond 200 amu. Therefore, for satisfactory analysis in the mass range 1 - 200 amu, it would probably be sufficient to pulse the electron beam only and not resort to pulsing of the drawing-out or repeller voltage as is done in the Bendix spectrometer.

2. Deflection Method of Ion Selection

Figure 19 is a schematic of the arrangement for selecting ion bunches by an electrostatic-deflection method. The ion beam passes between the two deflecting plates, of length, ℓ_1 across which a voltage pulse is applied with the frequency of and synchronized with the electron-beam chopping pulses. The duration of a deflection pulse is just enough to deflect ion bunches of a particular mass from the beam. These bunches will be collected by an ion cup displaced laterally from the beam-collector ion cup by the distance, c. The plate length, ℓ_1, must be long enough

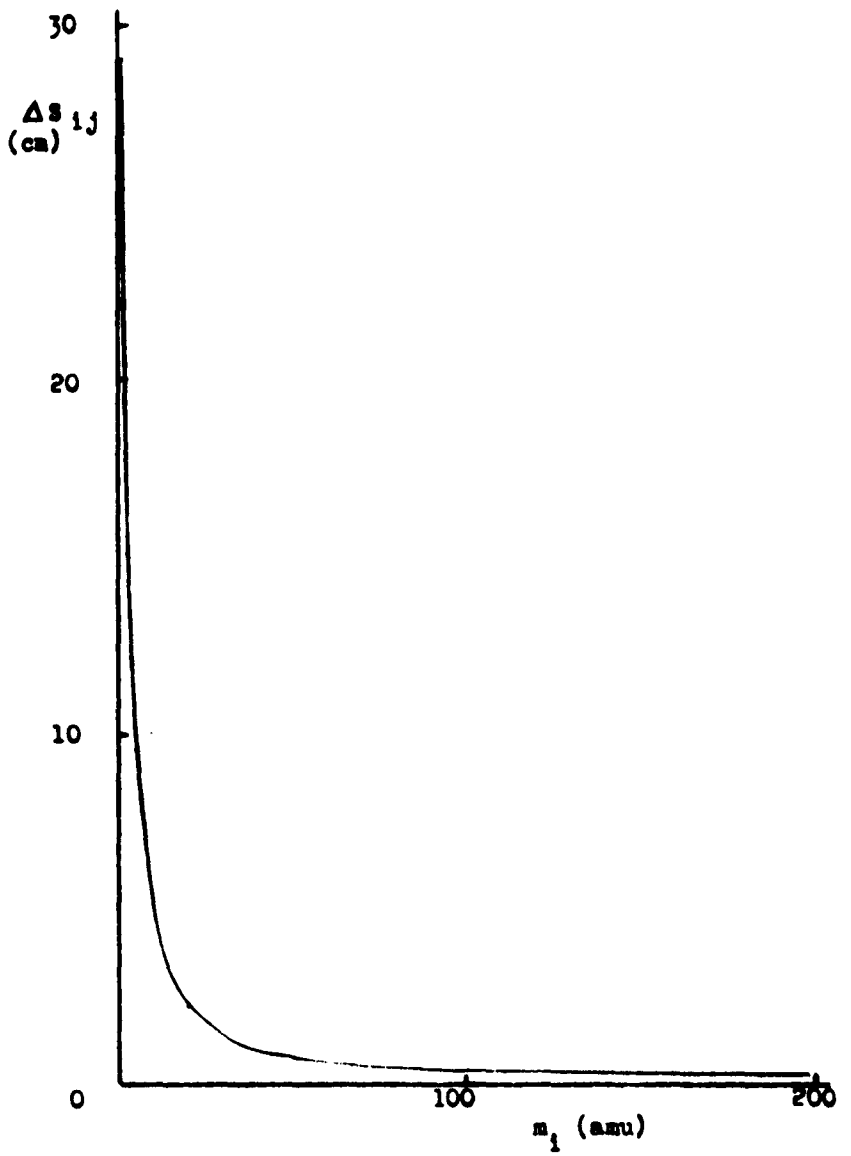

Figure 18. Ion bunch separation, ΔS_{ij}, versus mass, m_i.

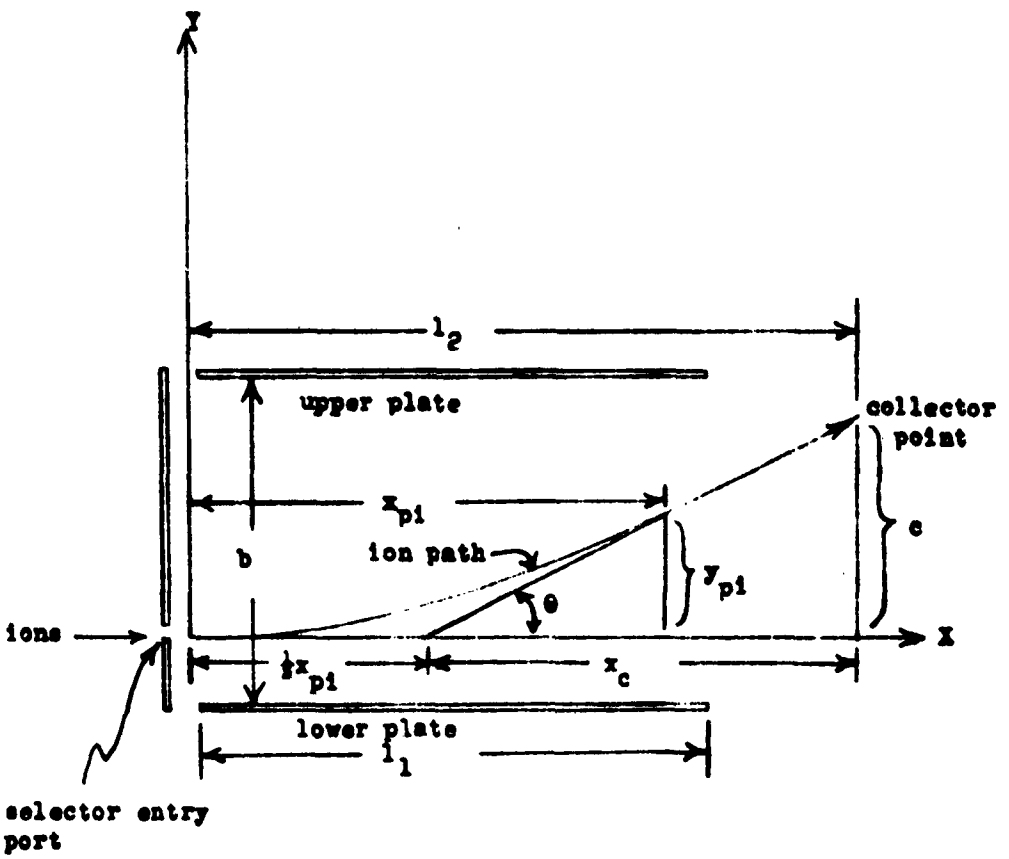

Figure 19. Schematic for ion-selection analysis.

so that the ion bunch is still between the plates when the deflecting voltage is cut off; and cut-off must occur before the following ion bunch (whose mass is greater by 1 amu) reaches the field produced by the plates. Thus, the deflection-pulse duration, t_{pi}, is defined by

$$t_{pi} \leq \frac{S_i'}{v_i} + \frac{\Delta S_{ij}}{v_j} \tag{11}$$

where S_i' is the length of bunch, i, and is defined by equation (7). The distance between successive bunches, i and j, is equal to ΔS_{ij} which is given by equation (10). Hence, from equations (7), (10) and (11),

$$t_{pi} \leq \Delta t + \frac{d}{\sqrt{\frac{2eV}{m_i}}} \left\{\sqrt{\frac{m_j}{m_i}} - 1\right\} - \frac{\Delta t}{2}\left\{\sqrt{\frac{m_j}{m_i}} + 1\right\}. \tag{12}$$

A plot of t_{pi} versus m_i is given in Figure 20 for a mass range, 1 - 200 amu, and is obtained by removing the inequality sign from equation (12).

For $m_i < 4$, the plate length must be greater than about 12 cm in order for the ions to remain within the deflecting field for the duration of the deflecting pulse, as defined by equation (12). If $m_i \leq 3$, ℓ_1 must be greater than about 23 cm which would require too long a drift space; that is, beam spread would make ion selection difficult and excessive space would be required for the instrument. For a mass range, 4 - 200 amu, and a plate length equal to 12 cm, a plot of V_{pi} is the deflecting pulse amplitude (in volts) which will cause ion bunches of mass, m_i, to be collected at c.

In Figure 19, the line tangent to the parabolic ion path at point X_{pi}, intercepts the X - axis at $X_{pi}/2$; hence

$$X_c = \ell_2 - Y_{pi} \cot \theta \tag{13}$$

where Y_{pi} is the lateral deflection of ions of mass, m_i, at the time the pulse is cut off. Thus

$$Y_{pi} = 1/2 \left(\frac{eV_{pi}}{m_i b}\right) t^2_{pi} \tag{14}$$

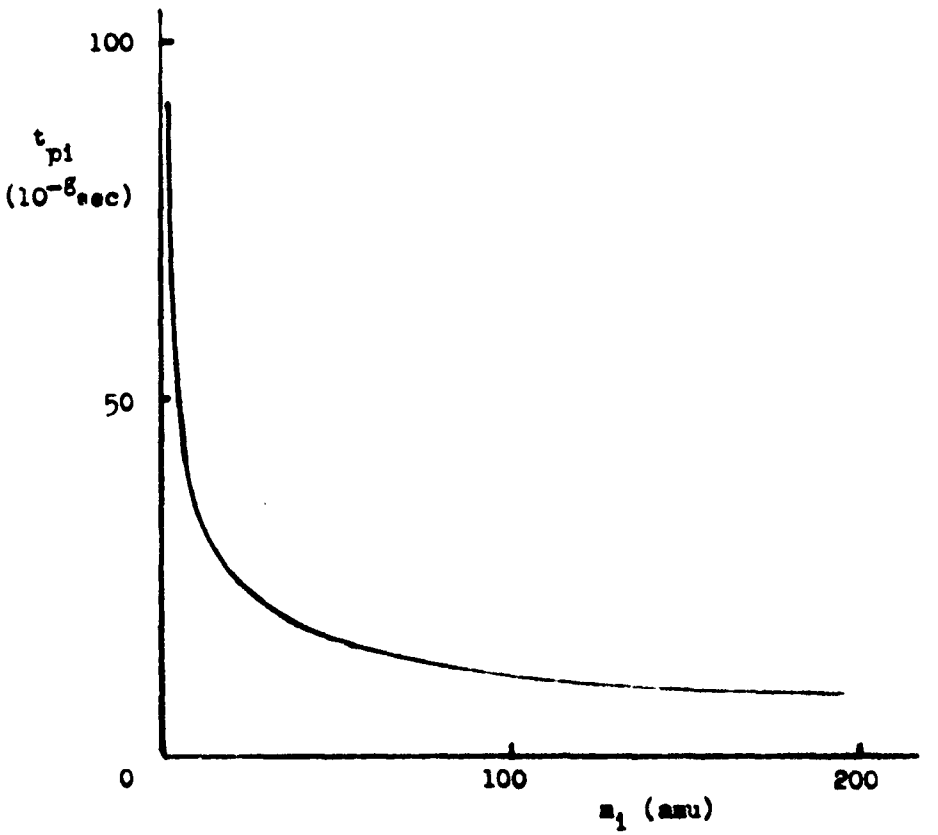

Figure 20. Deflection pulse length, t_{pi}, versus mass, m_i.

where b is the plate separation (and must be enough to keep ions from striking the upper plate). From equation (1) and the fact that $t_{pi} = X_{pi}/v_i$, it follows from (14) that

$$Y_{pi} = \frac{V_{pi}}{4Vb} X^2_{pi} \tag{15}$$

whence

$$\tan \theta = \frac{dY}{dx}\bigg|_{X = X_{pi}} = \frac{V_{pi} X_{pi}}{2Vb}. \tag{16}$$

Therefore, from (13),

$$X_c = \ell_2 - \left(\frac{2eV}{m_i}\right)^{1/2} \frac{t_{pi}}{2}$$

so that

$$c = X_c \tan \theta$$

or

$$c = \left[\ell_2 - \left(\frac{2eV}{m_i}\right)^{1/2} \frac{t_{pi}}{2}\right] \left(\frac{2e}{Vm_i}\right)^{1/2} \left(\frac{t_{pi}}{2b}\right) V_{pi}. \tag{17}$$

A plot of V_{pi} versus m_i, obtained from equation (17), is given in Figure 21; ℓ_2 has been set equal to 15 cm, b = 0.5 cm, and c = 1 cm. Values of t_{pi} are taken from the plot of Figure 20. Since V must be constant and equal to 10^3 volts for these values of t_{pi} to be used in equation (17), the delay time, τ_d, between the chopping pulses and the deflecting pulses must be varied to bring different mass numbers into register on the collector.

If the deflecting-plate length, ℓ_1, is set at 12 cm, then equation (17) is not strictly valid for $m_i < 4$ amu. However, it can be easily seen from equation (17) that the extra voltage needed to bring ions in this mass range to the collector is not appreciable.

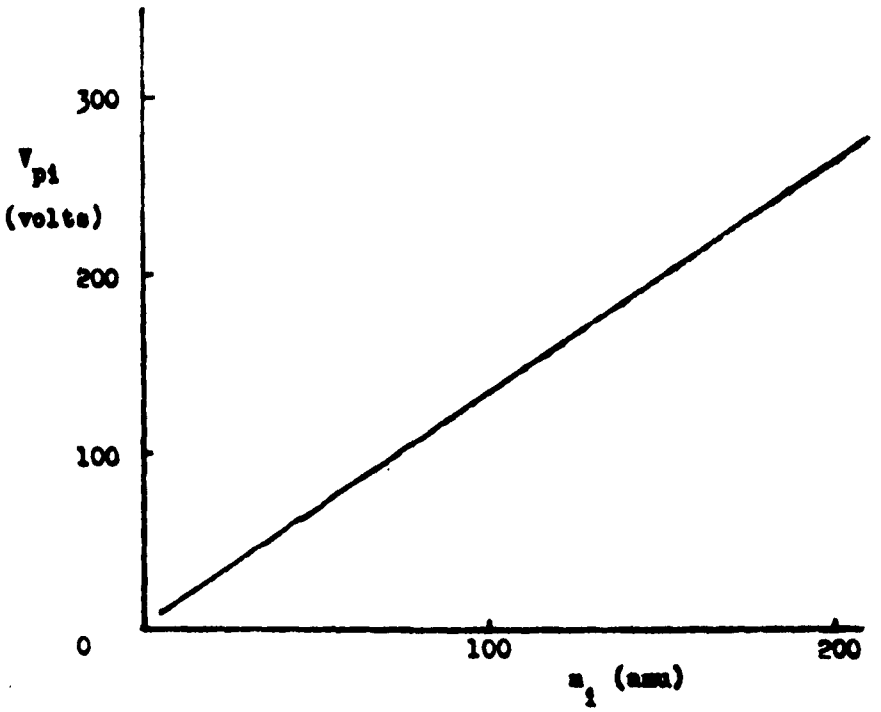

Figure 21. Deflection voltage, V_{pi}, versus mass, m_i.